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## **Radiation Testing of a Low Voltage Silicone Nuclear Power Plant Cable**

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## **Abstract**

This report summarizes the results generated in FY13 for cable insulation in support of the Department of Energy's Light Water Reactor Sustainability (LWRS) Program, in collaboration with the US-Argentine Binational Energy Working Group (BEWG). A silicone (SiR) cable, which was stored in benign conditions for ~30 years, was obtained from Comision Nacional de Energia Atomica (CNEA) in Argentina with the approval of NA-SA (Nucleoelectrica Argentina Sociedad Anonima). Physical property testing was performed on the as-received cable. This cable was artificially aged to assess behavior with additional analysis. SNL observed appreciable tensile elongation values for all cable insulations received, indicative of good mechanical performance. Of particular note, the work presented here provides correlations between measured tensile elongation and other physical properties that may be potentially leveraged as a form of condition monitoring (CM) for actual service cables. It is recognized at this point that the polymer aging community is still lacking the number and types of field returned materials that are desired, but Sandia National Laboratories (SNL)—along with the help of others—is continuing to work towards that goal. This work is an initial study that should be complimented with location-mapping of environmental conditions of Argentinean plant conditions (dose and temperature) as well as retrieval, analysis, and comparison with in-service cables.

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## NOMENCLATURE

BEWG	Binational Energy Working Group
CM	Condition Monitoring
CNEA	Comision Nacional de Energia Atomica
DED	Dose-to-equivalent Damage
DLO	Diffusion Limited Oxidation
DOE	Department of Energy
FY	Fiscal Year
IAEA	International Atomic Energy Agency
IEEE	Institute of Electrical and Electronic Engineers
LICA	Low Intensity Cobalt Array
LWRS	Light Water Reactor Sustainability
NA-SA	Nucleoelectrica Argentina Sociedad Anonima
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
SiR	Silicone Rubber
SNL	Sandia National Laboratories

# 1. INTRODUCTION

Nuclear energy is one industry in which the aging of safety-related materials and components is of concern and warrants further research [1], particularly as an increasing number of U.S. nuclear power plants (NPPs) are operating on extended licenses (beyond 40 years of age) [2]. To ensure the safe, reliable, and cost-effective long-term operation of NPPs, many systems, structures, and components should be evaluated through surveillance programs, modeling, predictive aging studies, or a combination of these approaches. Furthermore, as new analytical techniques and testing approaches are developed, it is imperative that we also validate, and if necessary, improve upon the previously employed Institute of Electrical and Electronic Engineers (IEEE) qualification standards originally written in 1974 [3]. Fortunately this challenging task has widespread support.

Today, the U.S. has several nuclear power plants already operating on extended licenses. Recent polling data obtained from the utilities indicate that the key concerns for potential aging phenomena are cables and piping [1,2]. As such, Sandia National Laboratories (SNL) is collaborating with colleagues in other Department of Energy (DOE) and Department of Commerce (DOC) laboratories, the U.S. Nuclear Regulatory Commission (NRC), industry, and partners abroad as part of a collaborative approach to clearly identify: 1) what work has been done in the past to investigate cable degradation, 2) what are the relevant cable aging conditions in plant environments (e.g. temperature, humidity, dose/dose rates), 3) what are the highest priority experiments required to model and therefore estimate the remaining lifetimes of existing cables, and 4) identify potential sources to retrieve service cables which could test current assumptions for aging processes.

The goal of the study was to leverage existing resources (the Low Intensity Cobalt Array (LICA) facility at SNL, Albuquerque, NM, USA) to generate and share mutually beneficial polymer aging data, as agreed upon in the US-Argentine Binational Energy Working Group (BEWG). SNL's contributions reflect only one facet of a broader US-Argentine collaboration, which was facilitated by the DOE, and directed by the U.S. State Department. Because both US (approximately 5% of US NPPs employ low voltage silicon rubber (SiR) cable insulations [4]) and Argentine (Atucha I, a pressurized Heavy Water Reactor located in Buenos Aires Province) NPPs employ low voltage SiR cable insulations, the data in this report complement existing SiR cable insulation data [5,6] and can be collectively used in the development of lifetime predictive models for SiR cable insulations. Note that this investigation was not intended to perform an exhaustive long-term polymer aging study on SiR cable insulations; the aging conditions were mutually negotiated by Comision Nacional de Energia Atomica (CNEA) and SNL staff based on existing data [5,6].





## 2. EXPERIMENTAL

### 2.1. Materials

An approximately 1.5 m section of an unused, stored, low voltage SiR cable was received from the CNEA, see Figure 1. The SiR cable (both jacket and low voltage insulations are apparently the same elastomer type with 4.3 mm and 0.6 mm wall thicknesses, respectively) had 34 insulated conductors and was about 30 years old; the cable manufacturer was not readily apparent but is believed to be from the same manufacture as those cables employed in Atucha I. This particular cable was stored at ambient conditions in a warehouse, but discussions with CNEA reveal that analogous service cables are exposed to both gamma radiation and elevated temperatures.



**Figure 1 - Silicone rubber cable specimen (scale in centimeters); photo taken from previously published report [6].**

### 2.2. Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry (DSC) was used to screen for any thermal transitions related to crystallinity. Experiments were performed on a TA Instruments DSC Q200. DSC sample specimens on the order of 10 mg were used. The nitrogen gas flow was maintained at ~20 mL/min. The samples were run at a ramp rate of 10 °C per minute. Temperature and enthalpy were calibrated with the commonly used indium standard.

### 2.3. Accelerated Aging

Cable specimens from CNEA were aged in a combined radiation-thermal environment between  $39 \pm 2$  Gy/h and  $37 \pm 2$  Gy/h, at the beginning and end of the radiation exposure, respectively, at 100 °C. Aging was conducted for a total accumulated dose of about 135 kGy. The dose rate was adjusted from  $33 \pm 2$  Gy/h [ $\text{CaF}_2$ ] by employing a correction factor of 0.84, which compensates for the absorption at high photon energies [7]. It should be noted that this correction factor is appropriate for hydrocarbon based absorptivity, but for consistency with previous studies at SNL, is used in this study of SiR cable insulations. Any future studies should

consider reevaluation of the appropriate correction factor for absorptivity of silicone based materials. To account for the decay rate of  $^{60}\text{Co}$  during the 3600 h experiment, an average dose rate of  $38 \pm 2\text{Gy/h}$  was employed for all dose calculations. Specimens were removed from the Low Intensity Cobalt Array facility (LICA, SNL, Albuquerque, NM, USA) at varying points in time for thermal, chemical, and mechanical analysis [8].

## 2.4. Tensile Testing

Cable insulation specimens for tensile testing were carefully stripped from their metal conductor prior to aging. All insulation specimens were aged as tubes that were measured to be  $\sim 150$  mm in length. Tensile testing (5.1 cm initial jaw separation, 12.7 cm/min strain rate) was performed on an Instron 5564 series equipped with pneumatic grips and extensometer clips that enabled direct ultimate tensile elongation values to be obtained. Tensile studies were usually performed in triplicate for each time period; control specimens were periodically tested to demonstrate the intrinsic variation in tensile elongation for the unaged material (see Figure 3).

## 2.5. Gel Content and Solvent Factor Uptake Analysis

Solvent factor uptake measurements were performed by refluxing a known weight ( $w_o$ ) of cable insulation in xylenes approximately eight hours. The swollen specimens recovered from the solvent ( $w_s$ ) were weighed to determine the mass of the absorbed solvent. Subsequently, the ‘wet’ specimens were dried in a vacuum oven held at  $80^\circ\text{C}$  overnight to achieve a constant final weight. The final weight ( $w_f$ ) of the insulation was then recorded. The recorded solvent uptake factor is equal to the ratio of  $w_s$  to  $w_f$ . Comparatively, the gel content is equal to the ratio of  $w_f$  to  $w_o$ .

$$\text{Solvent Factor Uptake} = \frac{w_s}{w_f}$$

$$\text{Gel Content} = \frac{w_f}{w_o}$$

$w_s$ = swollen weight

$w_f$ = final weight; dried via vacuum

$w_o$ = initial weight

## 2.6. Density

Archimedes’ principle was employed to measure the macroscopic densities of as received and laboratory aged cable insulations [9-11]. In short, specimens of approximately 50 to 200 mg were weighed both in air and then in isopropanol on a microbalance. Density calibrations were performed using glass calibration spheres of accepted density.

### 3. RESULTS AND DISCUSSION

#### 3.1. Differential Scanning Calorimetry

DSC was performed on the as received SiR cable insulations. As expected for an amorphous polymer, neither the jacket nor the insulation material showed any thermal transitions of relevance to this aging study. This was observed for multiple samples. However, a small thermal transition between 80 and 120°C was noticeable for an individual SiR sample, which after wiping the insulation with an isopropanol moistened tissue was no longer detectable. We believe that isolated insulation specimens may contain small surface contamination, which is barely detectable in a DSC scan. Figure 2 shows the DSC scans for SiR samples in comparison with commonly encountered polyolefin based insulation materials (cross linked polyolefin and ethylene propylene rubber -XLPO, EPR).

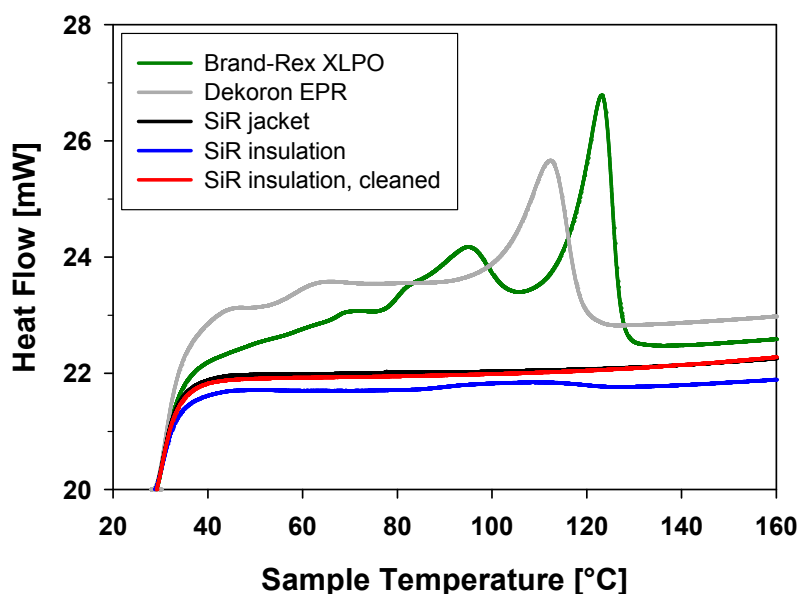
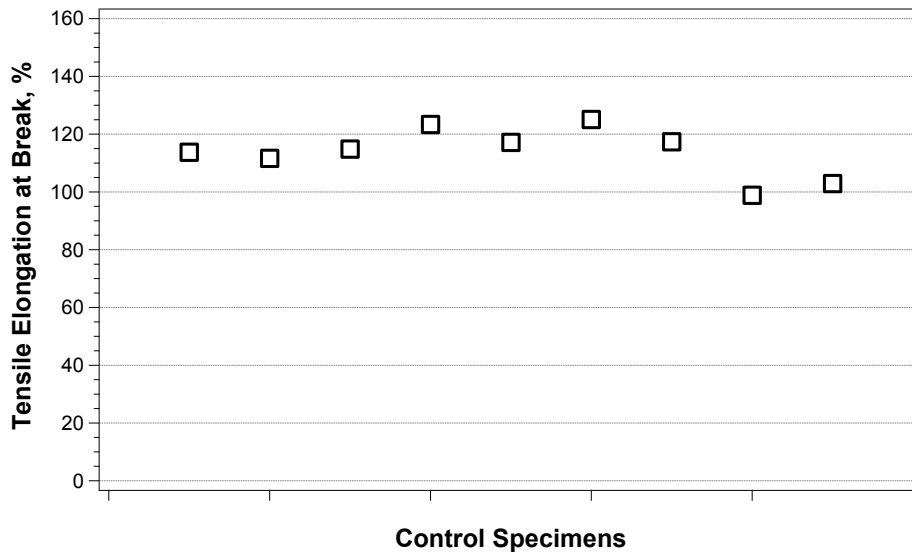


Figure 2 - Differential Scanning Calorimetry (DSC) scan of the as-received SiR cable insulation and comparison with XLPO and EPR.

#### 3.2. Tensile Testing

Tensile elongation at break for the as-received cable insulation was measured to be  $114 \pm 9\%$  at SNL, which suggests a substantial amount of “life remaining” [3], however the initial specification/qualification demands are unknown. Comparatively, previous measurements of the same SiR cable insulations, performed at CNEA, determined the tensile elongation at break to be  $\sim 175\%$ . Varying results could be due to the fact that CNEA does not employ extensometers while measuring tensile properties to quantify true strain.



**Figure 3 - Ultimate tensile elongation data for as-received SiR cable insulation. The abscissa reflects the individual control samples.**

Figure 4 shows the degradation of tensile elongation at break with increasing dose (and time) for the SiR cable insulation. Degradation to ~50% elongation at break (absolute) occurs after exposure to ~110 kGy when maintained at 100 °C. Figure 5 shows the normalized tensile elongation at break decay as a function of dose for SiR cable insulations exposed at both SNL and CNEA (dose rate = 15 kGy/h, T ~23 °C) [6]; note that the SNL data obtained at the highest total dose consists of three overlapping points. Albeit the decay in tensile elongation at break is similar from 0 Gy to ~20 kGy, the curves arguably diverge and could be attributed to 1) the temperature difference between both experiments and 2) diffusion limited oxidation (DLO) for the cables exposed to a very high dose rate at CNEA (~15 kGy/h), and 3) dose rate effects that result in degradation mechanism changes. Future assessment of the SiR cable insulations exposed to radiation at CNEA could validate the DLO claim (e.g., to quantify edge effects through modulus profile measurements [9-11]). However, oxygen permeability in silicone is generally high and oxidation rates are rather low, therefore DLO may not be a contributing factor.

Japan Nuclear Energy Safety Organization Safety Standard (JNESS) performed simultaneous thermal-radiation aging experiments on SiR cable insulations from three varying manufacturers [5]. Because each of the SiR cable insulations varied in initial tensile elongation properties (aside from testing methodologies, i.e. extensometer use), one may compare these data by generating a dose-to-equivalent damage (DED) chart. Figure 6 shows simultaneous thermal-radiation aging data for SiR cables aged at 100 °C with varying dose rates, including data from the literature [5]. The CNEA data is omitted from the plot because it was not performed at 100 °C. Future efforts to develop predictive aging models for SiR cable insulations could leverage these data, along with additional experiments, and approximations regarding the environmental conditions service cables are exposed to (e.g., temperature, dose rate, expected service life).

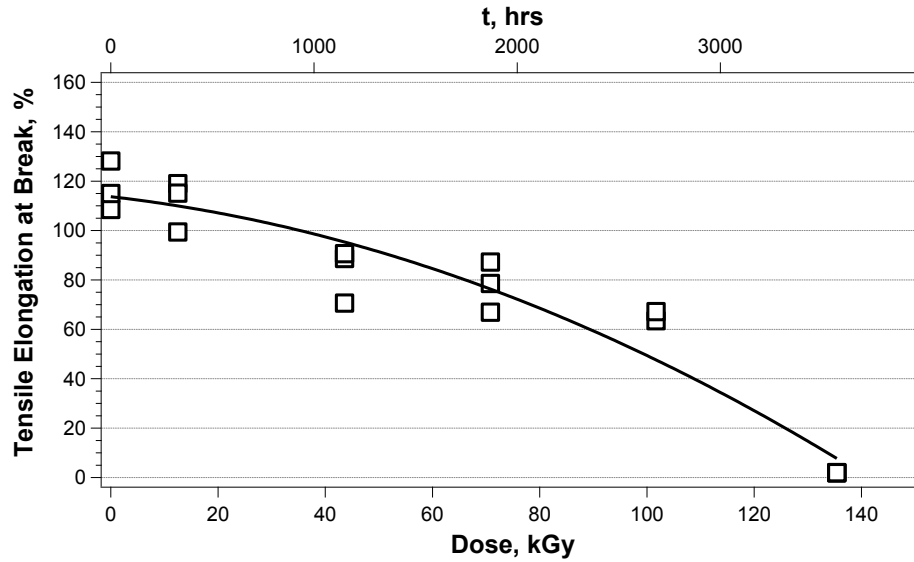


Figure 4 - Ultimate tensile elongation data for SiR cable insulations aged at 100 °C and ~38Gy/h.

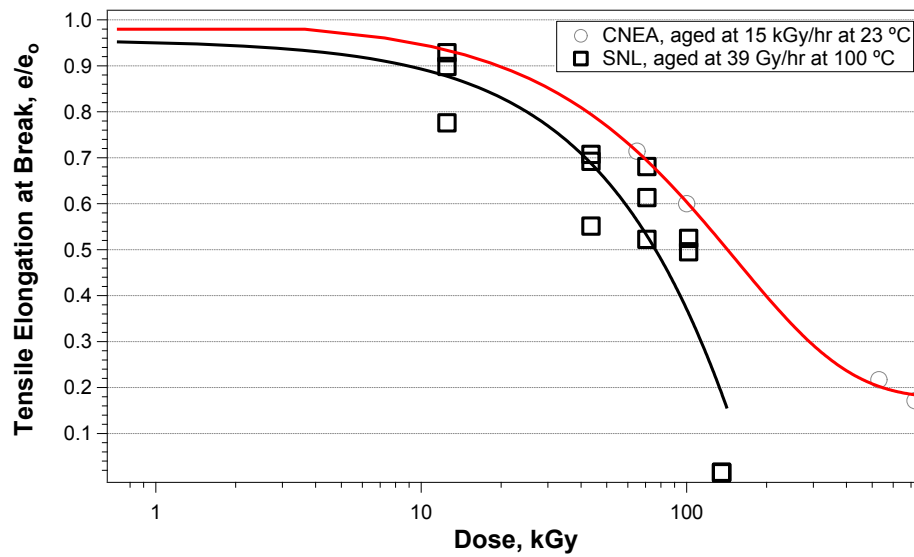
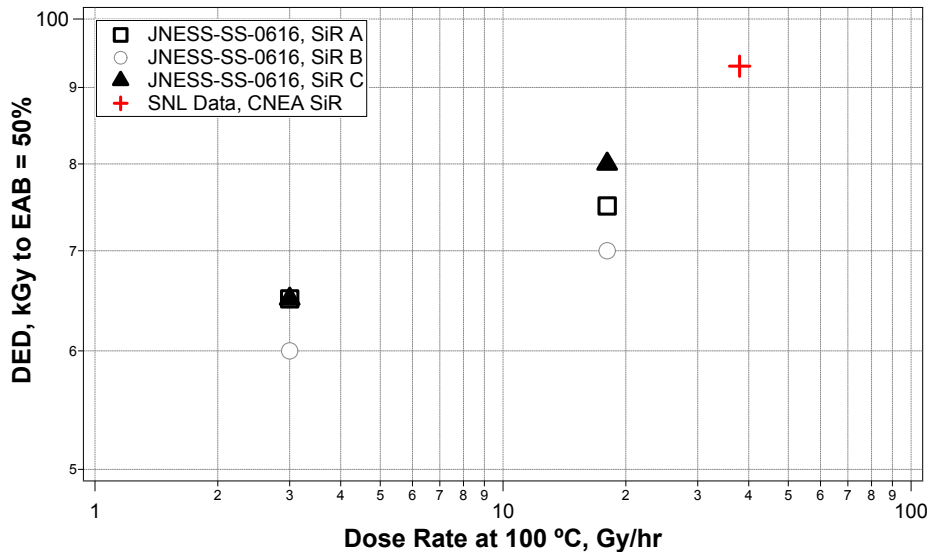


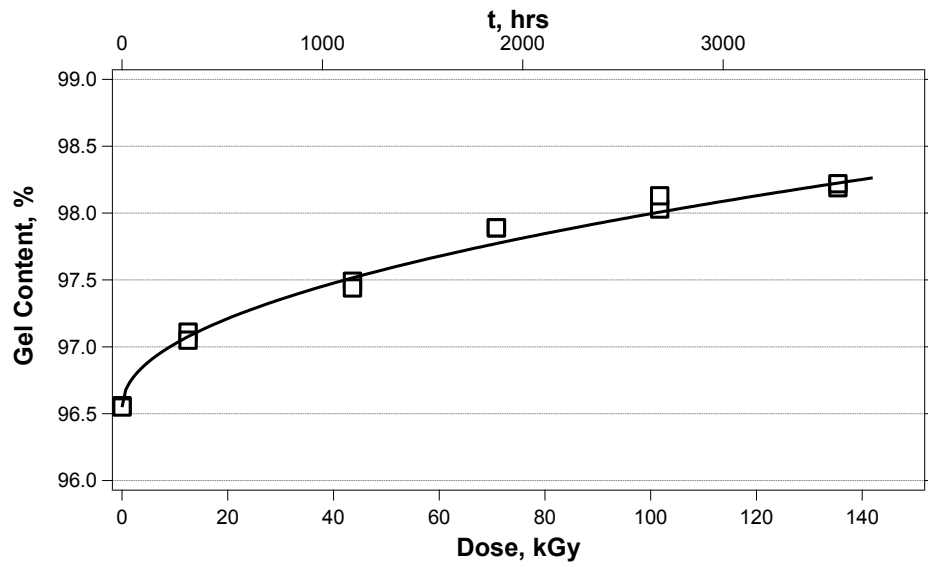
Figure 5 - Ultimate tensile elongation data for SiR cable insulations aged by SNL (100 °C and ~38 Gy/h) and CNEA (23 °C and ~15 kGy/h) [6].



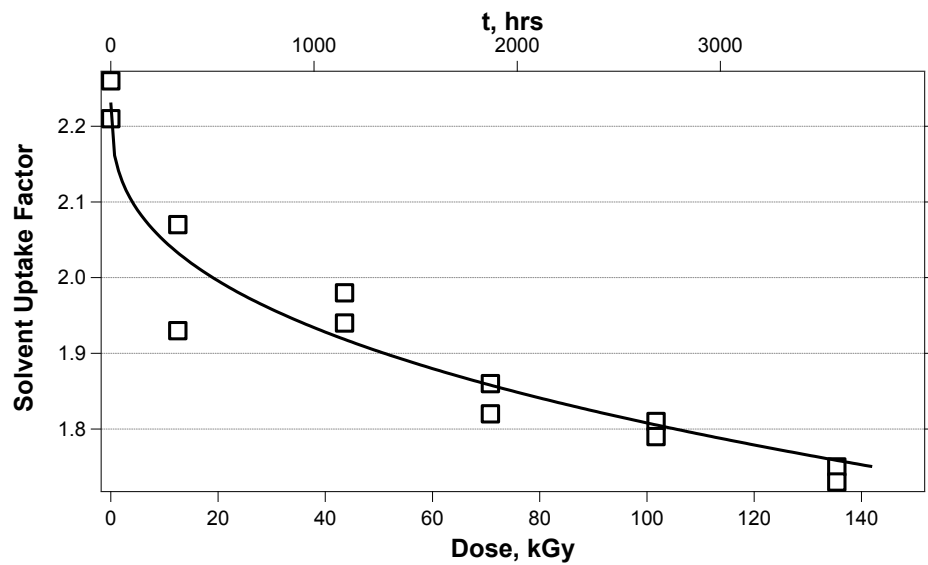
**Figure 6 – Dose-to-equivalent damage data (DED = 50%) for previously published data [5] plotted with SNL data discussed in this report.**

### 3.3. Gel Content and Solvent Uptake Analysis

To develop a better fundamental understanding of what chemically occurs during simultaneous thermal/radiation aging of the silicone rubber insulations, gel and solvent uptake analysis was performed. Figure 7 shows that the virgin cable has very high initial gel content (~96.5%); nevertheless, as the aging time and dose increase, the gel content also increases in a subtle manner, indicative of additional crosslinking despite an originally heavily crosslinked material. The observed gel content and solvent uptake factor (see Figure 8) behaviors clearly suggest that crosslinking is occurring as a function of aging; however, the change is very small (arguably ~2-3%). A much larger data set would be required to understand the experimental variability and how that relates to the small changes observed.



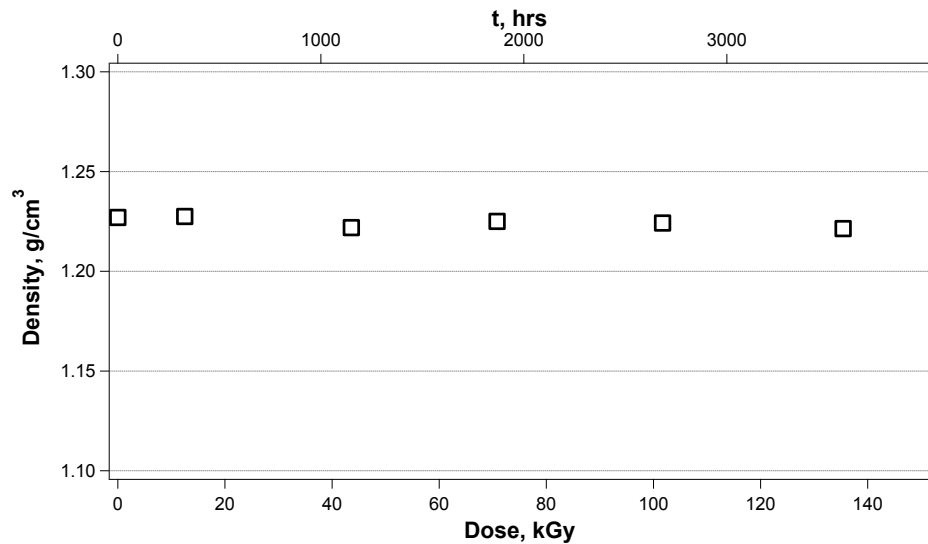
**Figure 7 - Gel content data for SiR cable insulations aged at 100 °C and ~38 Gy/h.**



**Figure 8 - Solvent uptake factor data for silicone rubber cable insulations aged at 100 °C and ~38 Gy/h.**

### 3.4. Density

The densities of the virgin and aged SiR cable insulations were also measured. Figure 9 shows the density is constant (within experimental error) for the aging conditions studied out to where the cable is no longer useable (based on reduced tensile elongation). As previously demonstrated, these new data confirm that density is not sensitive enough to be leveraged for CM for this material [9].



**Figure 9 - Density data for silicone rubber cable insulations aged at 100 °C and ~38 Gy/h.**



## 4. CONCLUSIONS

Preliminary screening studies have been performed to assess virgin SiR cable insulations, analogous to those employed by CNEA in Atucha I. As such, much work is still warranted e.g., location-mapping of environmental conditions of plant conditions (in progress), as well as retrieval, analysis, and comparison with in-service cables (planned for life extension of Atucha I). These would support the goals to develop and validate predictive models of the long-term aging of these cable material types, and develop suitable condition monitoring techniques. Completion of more extensive characterization tasks were outside the scope of this study.

Basic mechanical and chemical aging data measured for the SiR cable insulation offered generic trends to evaluate aging behaviors of key cables analogous to service cables in combined thermal/radiation environments. Future analysis of these data and collaboration through the US-Argentine BEWG may result in further studies and opportunities to perform accelerated aging on actual service cables. Of the CM techniques employed in this study, solvent uptake factor analysis, despite only small changes due to an initial high crosslink state, appeared to be the most promising CM technique in this scoping study. SNL will strive to use these and other CM techniques in polymer aging programs to aid the development of future in-service diagnostic abilities.



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